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# High-Confinement, High- $Q$ Microring Resonators on Silicon Carbide-On-Insulator (SiCOI)

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**Abstract**—We realize silicon carbide-on-insulator platform based on crystalline 4H SiC and demonstrate high confinement SiC resonators with sub-micron waveguide cross-sectional dimension. The obtained  $Q$  (57,000) is the highest  $Q$  reported for SiC microring resonators.

**Keywords**—(230.0230) Optical devices; (230.5750) Resonators; (190.4390) Nonlinear optics, integrated optics.

## I. INTRODUCTION

Tremendous effort has been made in the last decade to develop integrated nonlinear platforms using different materials including silica [1], silicon [2], Si<sub>3</sub>N<sub>4</sub> [3], Hydex [4], diamond [5], AlN [6], and AlGaAs [7]. Silicon Carbide (SiC) is also a promising material for nonlinear applications thanks to its high material nonlinearities. SiC has a refractive index of 2.6 around 1550nm, a wide bandgap (2.4~3.2 eV [8]), and a broad transparent window (0.37~5.6  $\mu$ m [9]). Its quadratic ( $\chi^{(2)}$ ) nonlinearity is ~30 pm/V, which is comparable to that of LiNbO<sub>3</sub> [10], while its Kerr ( $\chi^{(3)}$ ) nonlinearity is on the order of  $10^{-18}$  m<sup>2</sup>W<sup>-1</sup> [11], which is one order of magnitude larger than Si<sub>3</sub>N<sub>4</sub> [3]. Moreover, point defects in SiC are being exploited for single-photon sources for quantum applications [12], [13]. SiC photonic devices including photonic crystal, microdisk, and microring resonators have been studied for many years, and different applications have been demonstrated like second harmonic generation [14], parametric frequency conversion [15], self-phase modulation [16], and single-photon generation [17]. For nonlinear applications, not only high quality factor ( $Q$ ) resonators are critical components for efficient nonlinear applications due to an intra-cavity field enhancement, but high confinement waveguides are also desirable due to an effective nonlinearity enhancement. To realize integrated high-confinement waveguides in SiC, a SiC thin film of high quality should be fabricated with a low-index cladding (e.g. air or glass). Among more than 200 polytypes of different crystalline

SiC materials, 3C-, 4H- and 6H-SiC are the most common polytypes, which are commercially available. Such high confinement 3C-SiC photonic devices can be readily fabricated as 3C-SiC is available commercially in epitaxially grown films on silicon substrates. However, the growth-induced stacking defects result in a high material absorption loss. The highest  $Q$  demonstrated for 3C-SiC microring resonators is ~42,000 [18]. 4H- and 6H-SiC offer a higher crystal quality but are only available in bulk crystalline wafers. Smart-cut, a mature technology for silicon-on-insulator wafer fabrications [19], can be utilized to fabricate silicon carbide-on-insulator (SiCOI) wafers [20]. However, large dimension waveguides have been used in previous demonstrations [16],[21] to mitigate the scattering loss from rough waveguide sidewalls at the price of reduced effective nonlinearities. In this paper, we fabricate high-confinement 4H-SiCOI microring resonators using optimized patterning processes and demonstrate the highest  $Q$  (~57,000) for SiC microring resonators.

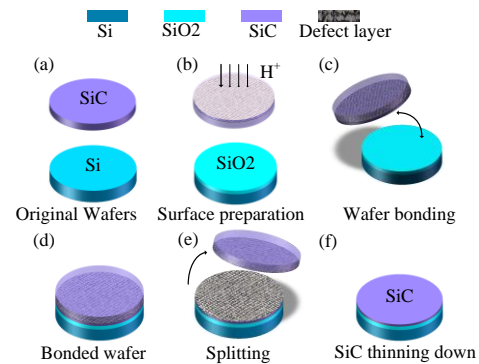


Fig. 1. (a) SiC and silicon carrier wafer. (b) H<sup>+</sup> ion implantation into bulk crystalline SiC wafer and thermal oxidation of silicon carrier wafer. (c) Wafer bonding between thermal oxidized silicon wafer and ion implanted SiC wafer. (d) Bonded wafer. (e) Splitting of SiC wafer after high temperature annealing and (f) SiCOI wafer after SiC layer thinning down.

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## II. FABRICATION

The fabrication process of the SiCOI wafer is shown in Figure 1. First, the 4H bulk SiC wafer was implanted with 170 keV  $H^+$  species.  $H^+$  peak concentration was simulated to be at 1.1  $\mu\text{m}$  under the wafer surface and micro-cavities (defects) are created along the peak concentration [22]. The silicon carrier wafer was thermally oxidized to grow a 2- $\mu\text{m}$  thick silicon dioxide layer. After cleaning of both wafers, they were bonded together by using direct wafer bonding. The bonded wafers were then annealed at around 850°C to split the thin SiC film from the bulk SiC wafer. The last step was thinning down of SiC layer. A common method is chemical mechanical polishing [23], which can remove defective SiC material and smooth the surface. Here, the SiC was thinned down from 1.1  $\mu\text{m}$  to 500 nm.

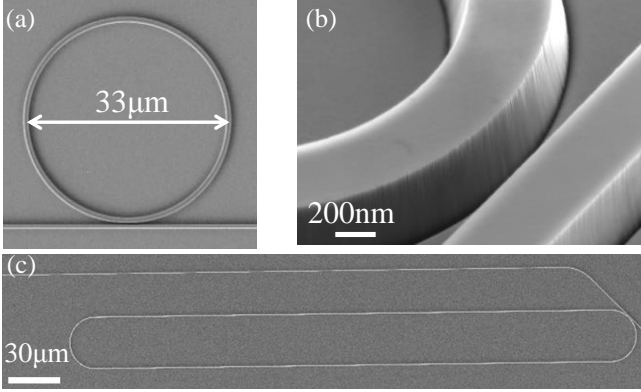


Fig. 2. Scanning electron microscopy (SEM) pictures of a fabricated microring resonator with a radius of 16.5  $\mu\text{m}$  (a) and its coupling region (b). (c) A 1004-  $\mu\text{m}$  long racetrack ring resonator.

The device fabrication on the SiCOI wafer started from electron beam lithography. A 600-nm thick electron-beam resist layer (hydrogen silsesquioxane) was spun on SiCOI wafer as the etching mask. The device pattern was transferred to the SiC layer in an inductively coupled plasma reactive ion etching machine using fluorine-based gases ( $\text{SF}_6$ ). Figure 2(a) shows a 16.5- $\mu\text{m}$  radius (1THz) microring resonator and figure 2(b) shows the coupling region of the microring resonator with a coupling gap of 300 nm. Figure 2(c) is a 1004- $\mu\text{m}$  long racetrack ring resonator.

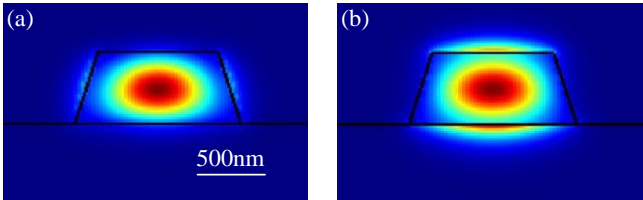


Fig. 3. Simulated mode profile for the fundamental TE (a) and TM (b) modes with effective areas of 0.32  $\mu\text{m}^2$  and 0.30  $\mu\text{m}^2$ .

The fabricated SiC waveguides are 500 nm high and 680 nm wide, and the mode profiles for fundamental transverse electric (TE) and transverse magnetic (TM) modes are shown in figure 3(a) and 3(b), respectively. Since the effective nonlinearity  $\gamma$  is highly dependent on the effective mode area  $A_{\text{eff}}$  as expressed by the equation  $\gamma = 2\pi n_2 / \lambda A_{\text{eff}}$ , where  $n_2$  is the nonlinear refractive index of SiC [11] and  $\lambda$  is the operating

wavelength. Thanks to the strong light confinement in such a sub-micron dimension waveguide, a large effective nonlinearity at the order of 10  $\text{W}^{-1}\text{m}^{-1}$  can be expected.

## III. CHARACTERIZATION

To characterize the performance of SiCOI devices, we fabricated straight waveguides with different lengths and microring resonators including 16.5- $\mu\text{m}$  radius microring resonators and 1004- $\mu\text{m}$  long racetrack resonators. Figure 4 shows the measured insertion losses of waveguides with different lengths for fundamental TE and TM modes. The estimated linear losses for straight waveguides are 10 dB/cm and 9.3 dB/cm for TE and TM modes, respectively.

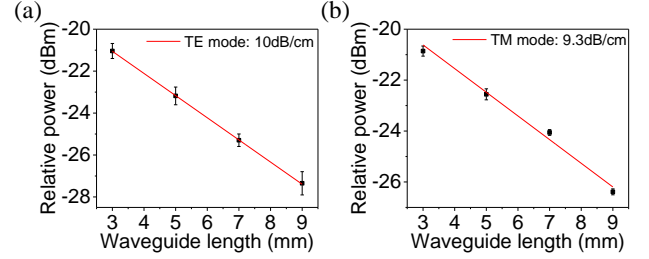


Fig. 4. Measured insertion loss of SiCOI waveguides with different lengths for the fundamental TE (a) and TM mode (b).

Figure 5 shows the normalized transmission spectra of 16.5- $\mu\text{m}$  radius microring resonator (figure 5(a,b,e,f)) and 1004- $\mu\text{m}$  long racetrack ring resonator (figure 5(c,d,g,h)). The resonances were fitted with Lorentzian curve. As those tested devices work in under-coupling region, the intrinsic Q factor can be calculated as  $Q_{\text{int}} = 2Q_{\text{load}} / (1 + \sqrt{T})$  [25], where  $Q_{\text{load}}$  is the loaded Q and T is the transmission normalized to the maximum value of fitting curve. The free spectrum range (FSR) was measured as 1.008 THz and 0.956 THz for fundamental TE and TM modes in 16.5- $\mu\text{m}$  radius microring resonators, respectively. 103.8 GHz and 98.8 GHz FSR were measured for TE and TM modes in 1004- $\mu\text{m}$  long racetrack ring resonators, respectively. We achieve intrinsic Q factor of 50,000 and 51,000 for fundamental TE modes in 16.5- $\mu\text{m}$  radius microring resonator and 1004- $\mu\text{m}$  long racetrack ring resonator, respectively. Q factor of 48,000 and 57,000 are obtained for fundamental TM modes in 16.5- $\mu\text{m}$  radius microring resonator and 1004- $\mu\text{m}$  long racetrack ring resonator, respectively. The achieved 57,000 is the highest Q factor reported in crystalline SiC microring resonators. Since the 1004- $\mu\text{m}$  long racetrack ring resonator consists of 16.5- $\mu\text{m}$  radius curved waveguide and 900  $\mu\text{m}$  straight waveguide, we also extract the linear loss of straight waveguide part for TE and TM modes and 9.8 dB/cm and 9 dB/cm were obtained, respectively. The extracted linear loss for straight waveguides matches quite well with measured straight waveguide loss, which confirms the measurement results of straight waveguides.

## IV. CONCLUSION

High confinement waveguides with sub-micron cross-sectional dimensions (500×680  $\text{nm}^2$ ) and microring resonators in the SiCOI platform was demonstrated. a high Q of 57,000 for a 1004- $\mu\text{m}$  racetrack resonator was obtained, which is the highest reported Q for crystalline SiC microring resonators.

The demonstrated high  $Q$ , high confinement microresonators are promising in nonlinear applications, such as frequency comb generation. To improve the performance of SiCOI devices, the dry-etching process can be optimized to reduce sidewall roughness-induced scattering. Furthermore, the crystalline quality of SiC thin film can be improved by  $H^+$  implantation at elevated temperature [25] or post annealing at high temperature.

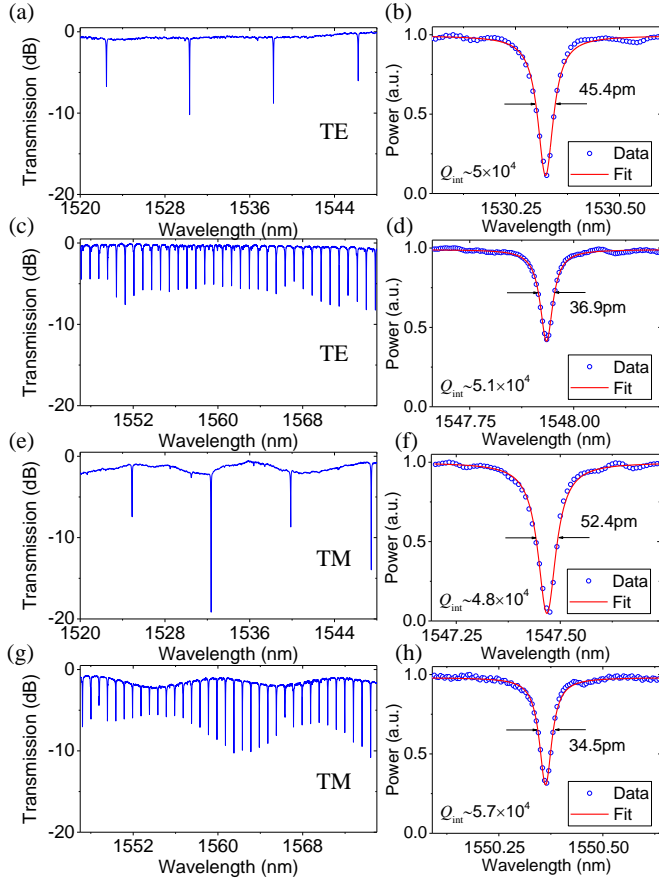


Fig. 5. Measured (normalized) transmission spectra for 16.5- $\mu$ m radius microring resonators (a, b, e, f) and 1004- $\mu$ m long racetrack resonators (c, d, g, h) for the fundamental TE mode (a-d) and TM mode (e-h).

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